Primordial Black Hole Binaries as a Source of Gamma-Ray Bursts and of a High-Frequent Gravitational Radiation

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Abstract

Ultracompact primordial black hole binaries (PBHB's) with masses $m > 10^{16} g$ are considered here. If PBHB's contribute significant part of the dark matter of the Galaxy one can expect an existence of high-frequent non-thermal diffuse gravitational radiation with flux of $1\ erg\ cm^{-2}\ s^{-1}$. The possibility of coalescence of the PBHB's in Galaxy's halo to be a source at least of a part of gamma-ray bursts (GRB) observed is discussed. The energy flux of gravitational radiation from those GRB should exceed the energy flux of γ-radiation by 7-8 orders of magnitude. The possibility of observation of PBHB through detection of the gravitational radiation burst coincident with GRB is emphasized. The PBHB also can be observed detecting a stationary gravitatonal radiation in the frequency range $> 10^4\ Hz$ and observing a high-frequent pulsation of a source's brightness in microlensing effects in the Galaxy's halo.

An existence of primordial black holes (PBH) was predicted in [1]. As it is known PBH may burn in many models of evolution of early Universe [2, 3, 4, 5], and the initial mass distribution is strongly model-dependent [5, 6]. More often it appears to be close to $n(m) \sim m^{-5/2}$, but some models suggest extended number of PBH with $m > 10^{17}g$ - it allows one to consider PBH as a main source of the dark matter of the Universe [6]. In the last years a possibility of existence of the PBH with masses up to $0.5M_\odot$ is intensively discussed - these PBH are the best candidates as a lensing bodies in the halo of Galaxy. PBH with $m < 10^{15}g$ must evaporate before our epoch. Nevertheless, assuming distributions of PBH and barionic (visible) matter in the Universe to correlate one can predict the modern density of PBH in the Galaxy to be more or less high. If η is a part of PBH with an average mass $\overline{M}$ in the density of dark matter then average distance between them is ($H \equiv H_0/100s^{-1}Mpc^{-1}$ - modern Hubble's constant):

$$\overline{r} \sim 4{\cdot}10^{18}\left(\frac{\overline{M}}{\eta M_\odot}\right)^{1/3}(\Omega H^2)^{-4/3}\ cm \tag{1}$$

Moreover, a capture of PBH by Solar system may result in increase of PBH's concentration in the vicinity of the Sun. In this case PBH may appear more closer to the Earth.

At final stage of evolution ($m < 10^{14}$) when hadron burning is possible the evaporation of PBH looks like an explosion observed at far distance as burst of γ-rays in the energy range $E_\gamma \sim 0.1 - 100$ GeV during $\tau \sim 10 - 50$ ms [7] relating to some part of observed GRB's. Note, that the energy, the duration and the spectrum of the burst created by final explosion of PBH are unique and fixed, so most of GRB's which are very manifold cannot be reasoned by this mechanism. Besides, a substantial difficulty of evaporation model is that if all observed GRB's are due to PBH explosions then γ-luminocity of the Galaxy appears to be extremely high - in contradiction with observed one.

Usually PBH is considered as a single object. However, many astrophysical objects are observed to be a binary system. Calculations show [8] that at the epoch of matter-radiation equilibrium significant amount ($\kappa \sim 0.05 - 0.03$) of PBH can be captured into ultracompact binary systems due to their very close disposition. Accordingly to [8] after $T \sim 10^{10}$ years the part of binary systems with lifetime (before coalescence) $\tau \ll T$ is:

$$p(T,\tau) \simeq 0.04\frac{\tau}{T}\left(\frac{\overline{M}}{\eta M_\odot}\right)^{\frac{5}{148}} \tag{2}$$

For example, when $\eta = 1$, $\kappa = 0.1$, $M_\odot = 10^{18}g$, $\tau = 10^6 y$ then average distance between the Earth and nearest binary PBH is $\sim 10^{14}cm$. So it can be interesting to search observable effects caused by existence of such objects at same distances ($10^{14} - 10^{16}cm$).

If the distance between partners in a binary system is significantly greater than their gravitational radii (that is their relative motion is quasinewtonian) then for far observer it looks mainly like a source of a high-frequent gravitational radiation with the intensity [8]

$$I_g = \frac{32c^5}{5G}\left(\frac{M}{a}\right)^5 f(\epsilon) \tag{3}$$

Here $M \equiv \frac{G}{c^2} m_1 m_2/(m_1+m_2)$ is gravitational radius, and $f(\epsilon) \equiv (1-\epsilon^2)^{-7/2}(1+\frac{73}{24}\epsilon^2+\frac{37}{96}\epsilon^4), a$ and ϵ are parameters of the orbit. The intensity is determined by $\frac{M}{a}$ mainly, therefore at certain stage of evolution of the binary system it can appear close to the intensity of radiation of usual astrophysical binary objects. The main harmony in the spectrum is

$$\omega = 2\Omega_{rot} = \frac{2c}{a}\sqrt{\frac{m_1+m_2}{a}} \quad (4)$$

and one should note, that the relative intensity of higher frequencies increases with the excentricity ϵ increasing. The energy loose due to gravitational waves emission leads PBH to fall each to other during

$$\tau = t_{fall} - t_0 \simeq \frac{5}{256c}\frac{a_0^4}{M(m_1+m_2)^2} \quad (5)$$

Comparing (5) and (3) one concludes that PBH binary emits significantly only at very late stage of evolution. For example, when $m_1 = m_2 = 10^{17} g$ and $\frac{a_0}{M} < 10^9$ then intensity $I > 10^{10} Wt$ and $\tau < 5 \cdot 10^3$ years.

At distance r from binary system amplitude of gravitational wave is

$$h \sim \frac{M^2}{ar} \quad (6)$$

Therefore, at $h-\omega$ plot the point of radiation which can be observed near the Earth shifts to a high h and ω region during evolution of the PBH binary, thus moving to a coalescense line. In the Fig. 1 the lines of evolution of the radiation from symmetric $(m_1 = m_2 = 10^{16+n} g)$ at distance $10^{14} cm$ are plotted. Dotted lines express constant time left until coalescense.

At the moment of coalescense almost all energy is emitted as a short powerful burst of gravitational waves. This process cannot be described in the framework of quasinewtonian approach. To estimate amplitude and duration of the burst one usually extrapolates the problem of a probe body fall into a black hole. As a PBH binary has large orbital momentum and high rotational velocity, so when it merges one can expect the efficiency of emission to be high enough $\xi = E_g/(m_1+m_2)c^2 \sim 0.06-0.2$, closing to thermodynamical limit $\xi_{max} = 1 - 1/\sqrt{2}$. Thus, at the end of existence ultracompact PBH binary emits short (calculations give $\delta t \sim (10^1 - 10^3)\frac{M}{c}$) powerful ($E_g \sim 0.1(m_1+m_2)c^2$) burst of gravitational radiation. As a result the total gravitational radiation luminocity due to PBH binaries coalescense in the Galaxy where $M_{DM} \simeq 50 M_{Galaxy}$ is

$$I_G \simeq E_g(\kappa\eta M_{DM}/\overline{M} \cdot (P(T,\tau)/\tau) \simeq 0.001\kappa\eta M_{DM} c^2/T \sim \kappa\eta 10^{39}\ Wt \quad (7)$$

Therefore, if PBH binaries exist then the diffuse flux of non-thermal high-frequent $(\omega > 10^{10} Hz)$ gravitational radiation should be there in the Galaxy, which has the density

$$S_G \simeq I_G/4\pi {R_G}^2 \sim \kappa\eta \cdot 0.5\ erg\ cm^{-1}\ s^{-1} \quad (8)$$

Other possible effect of PBH binaries is an intensive particles creation and production of a fireball due to the energy being released during the merging. Since the amount of the energy is relatively large, the intensity of neutrino and γ-radiation can appear to be significant too even with a very small conversion efficiency. The part of energy ϵ_γ being converted to γ-radiation cannot exceed the value of $10^{-8}/\kappa\eta$, which provides almost all γ-luminocity of the Galaxy ($\sim 10^{31}$ W) assuming the dark matter to consist of PBH binaries. Besides, if parthers of PBH binaries have a mass $m \gg 10^{16}\ g$ the γ-evaporation is very small, and no problem of extremely high background of the diffuse γ-radiation is appeared.

At far distance the coalescense can be observed as neutrino and γ-bursts emited by relativistic fireball. The specific feature of this should be a homogeneous distribution in the Galaxy and hence a characteristic dependence of the number of sources on the flux observed above threshold ($\lg N \propto -3/2 \lg S$). But the total range of observed γ-bursts has not such distribution, i.e. the dependence $\lg N - \lg S$ deviates from simple 3/2 law. Moreover, several GRB's are observed to have extremely high redshift during optical counterpart, i.e. some of GRB's observed are obviously cosmological [12]. Therefore one cannot consider PBH binaries as unique source of GRB. Note, that the GRB's are divided on several classes. There are both relatively short bursts with $\Delta t_\gamma < 1s$ and long one with $\Delta t_\gamma > 10s$, and all GRB are widely distributed by hardness of spectrum.(ref to catalog to be here?) Besides, only long GRB with hard spectrum have significant deviation from -3/2 law. This can lead one to conclude that the origin of different GRB can differ too, in particular, significant part of GRB can burn in the Galaxy's halo. Thus, it's possible to suggest the fireball burning due to PBH merging in the halo to be a source of some part of GRB's. The merging rate in the halo can be estimated as

$$\nu \simeq (\kappa\eta M_{DM}/\overline{M})(P(T,\tau)/\tau) \simeq 10^{-6}\ \kappa\eta(M_\odot/\overline{M})\ s^{-1} \tag{9}$$

The rate of the GRB which can be observed near the Earth is determined by an observational threshold S_{min} and an average mass of halo's PBH: $\nu_{GRB} \simeq \nu(r/r_G)^3$, where $r \simeq (\epsilon_\gamma \cdot 0.1\overline{M}c^2/4\pi S_{min})^{1/2}$, and therefore

$$\nu_{GRB} \simeq 5 \cdot 10^2\ s^{-1}\kappa\eta(\epsilon_\gamma/10^{-8})^{3/2}(\overline{M}/M_\odot)^{1/2}(10^{-7}\ erg\ cm^{-1}\ s^{-1}/S_{min})^{3/2} \tag{10}$$

Taking into account that the rate of euclidian GRB's above $S_{min} = 10^{-7}\ erg\ cm^{-1}\ s^{-1}$ is $\sim 10^{-5}\ s^{-1}$ one can obtain a lower limit on average mass of PBH in the halo. For example, if $\eta = 1,\ \kappa = 1$ and $\epsilon_\gamma = 10^{-8}$ then $\overline{M} \geq 10^{18}$ g.

In frame of the model, as the γ-luminocity of the Galaxy is limited ($\epsilon_\gamma < 10^{-8}$) so the energy of gravitational radiation outburst from PBH binary coalescence may exceed the γ-burst energy by 8 orders of magnitude, that is, the gavitational energy fluence observed near the Earth during powerful GRB can be greater than $10^4\ erg\ cm^{-2}$.

One should note, that the discovery of very characteristic high-frequent gravitational radiation would prove an existence of ultracompact PBH binaries. But all existing and building gravitational detectors are oriented toward the search of low-frequent one [13], and so are not able to detect PBH binary through it's stationary radiation. Therefore, it looks very actual to develop the technique of detection of short intensive bursts and

stationary high-frequent gravitational radiation like electromagnetic or plasma detectors [11, 14]. For example, as it is shown at [14], if one uses electromagnetic field in the resonator with $Q = 10^{12}$ as an antenna one can detect gravitational wave down to $h \sim 10^{-27}$ at frequency 10^9 Hz. But one should note that the probability of detection of stationary radiation with so high frequency is extremely low due to short life time of compact binaries at this frequency (from 10^6 years for $m_1 = m_2 = 10^{16}$ g to 1 year for $m_1 = m_2 = 10^{20}$ g).

In principle, when one observes a microlensing effect with the binary consisting of the same mass PBH's appeared to be a gravitational lens, one should observe characteristic periodic pulsations of brightness of the source. The magnitude of the effect is estimated to be $\sim a^2/b^2$, where b is the distance of the center of binary masses from the direct line of sight, and the frequency of pulsations is equal to $2\Omega_{rot}$. Again, one should note, that the earth-based instruments are not able to detect such pulsations due to influence of atmosphere.

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References

[1] D. N. Page, S.W. Hawking. Astroph. J. **206**, 1 (1976)

[2] S. W. Hawking. MNRAS **152**, 75 (1971)

[3] V. A. Berezin, V. A. Kuzmin, I. I. Tkachev. Phys. Rev. **D43**, R3112-R3116 (1991)

[4] K. Jedamzik. Phys. Rept. **307**, 155-162 (1998)

[5] J. S. Bullock, J. R. Primack. Phys. Rev. **D55**, 7423-7439 (1997)

[6] J. MacGibbon. Nature **329**, 308 (1987)

[7] D. B. Cline, W. Hong. Astroph. J. **401**, L57-L60 (1992)

[8] T. Chiba, K. Ioka, T. Nakamura et al. Phys. Rev. **D58** (1998)

[9] P. C. Peters, J. Mathews. Phys. Rev. **131**, 435-447 (1963)

[10] S. L. Detweiler. Sources of Gravitational Radiation. 1979 Cambridge, pp 211-249

[11] I. Bichak, V. N. Rudenko. Gravitational waves in UTR and the problem of detection. MSU, Moscow, in Russian (1987)

[12] T. Piran. astro-ph/9810256

[13] A. Rudiger. Nucl. Phys. Proc. Suppl.) **B48**, 96-100 (1996)

[14] L. P. Grish'uk. Usp. Phys. Nauk **121**, 629- 656, in Russian (1977)

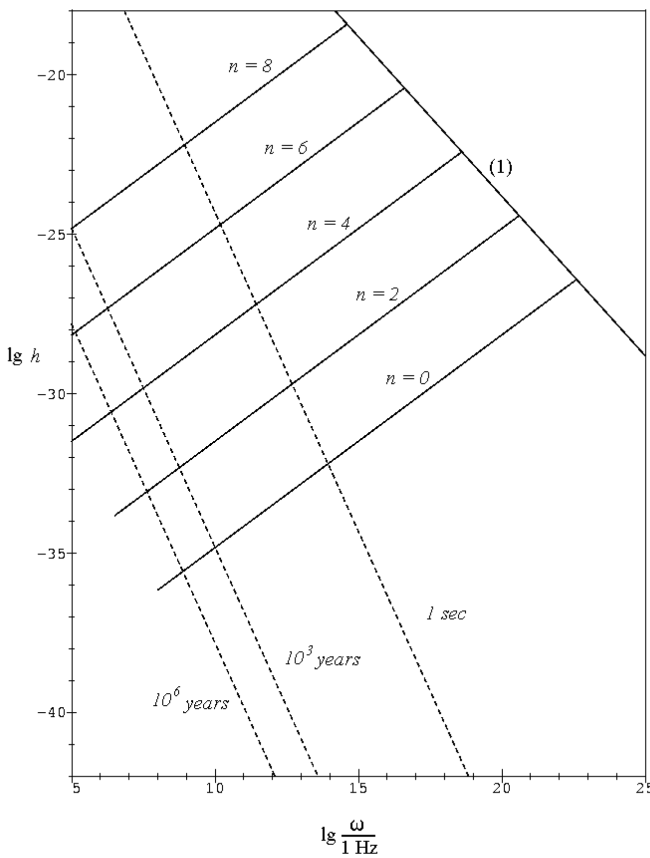

Figure 1: Lines of PBH binary evolution